

Quantum Superposition and Entanglement

EE599-001 & EE699-010, Spring 2026

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Physics vs. Comp. Eng.

- Some terms don't mean the same thing...
 - **Qubit**: mathematical vector in Hilbert space, realized by quantum properties
 - **State**: mathematical description of current condition of a time-evolving system
 - **Gate**: unitary transform of a wave function to evolve state over time
 - **Quantum Circuit**: a sequence of gates
 - **Adiabatic**: implies cyclic relaxation, not just thermodynamic reversibility

Quantum Wave Function: ψ

- $\psi(x)$ or ψ ... aka, **Psi**
 - Wave shape; solves Schrödinger equation
 - A wave function with a complex value, a **probability density function (PDF)**
 - $|\psi|^2$ is probability of a measurement outcome, normalized so sum over all possible is 1
- If $|\psi_1\rangle$ and $|\psi_2\rangle$ are potential solutions, then $a|\psi_1\rangle + b|\psi_2\rangle$ is also a solution

Superposition

- Suppose both $|\text{live_cat}\rangle$ and $|\text{dead_cat}\rangle$ are valid solutions
- Then $\sqrt{1/2}(|\text{live_cat}\rangle + |\text{dead_cat}\rangle)$ is a **superposition** in which they are equiprobable
- Does this mean a cat can be simultaneously live and dead? *This is math...*
- An equiprobable superposition of 1 and 0 is:
 $\sqrt{1/2}(|1\rangle + |0\rangle)$

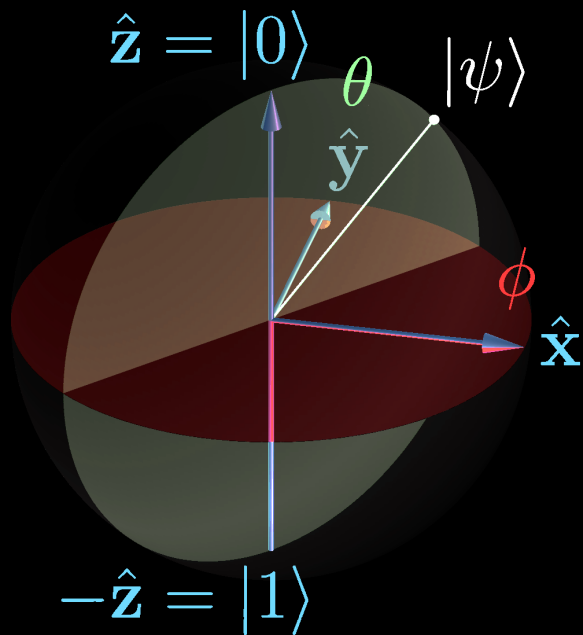
Interference

- Measurement gets you one value
- Wave functions can interfere
- Interference is largely about phase...
- We'll discuss this more later, but interference allows sampling the wave function in a way that acts more like summing than selecting

Decoherence

- Quantum wave functions are fragile
 - Any stray energy (noise) can interact
 - Phase information is particularly fragile (phase error \gg than wave function collapse)
- Main implications:
 - A superposed state does not last forever
 - Each operations adds noise & imprecision
 - Quantum computation inherently unreliable; error correction methods are needed

Bloch Sphere Qubit Model



$$\begin{aligned} |\psi\rangle &= \cos(\theta/2)|0\rangle + e^{i\phi} \sin(\theta/2)|1\rangle \\ &= \cos(\theta/2)|0\rangle + \\ &\quad (\cos \phi + i \sin \phi) \sin(\theta/2)|1\rangle \end{aligned}$$

where $0 \leq \theta \leq \pi$ and $0 \leq \phi < 2\pi$

- Visualizes wave function of a single qubit
- Probability by coordinates on sphere surface

Entanglement

- An equiprobable superposition of 1 and 0 is:
 $\frac{1}{\sqrt{2}}(|1\rangle + |0\rangle)$
- Suppose I have two such superpositions in two separate qubits:
 $\frac{1}{\sqrt{2}}(|1\rangle + |0\rangle)$ and $\frac{1}{\sqrt{2}}(|1\rangle + |0\rangle)$
- **Entanglement** simply sums the products:
 $\frac{1}{2}(|11\rangle + |10\rangle + |01\rangle + |00\rangle)$

Measurement

- What is **measurement**?
 - Collapse superposition to a single state?
 - Entangle observer with a single state?
- Returns a single state (*value*) *selected at random* with probabilities given by $|\psi|^2$
- Superposed value is not accessible after measurement

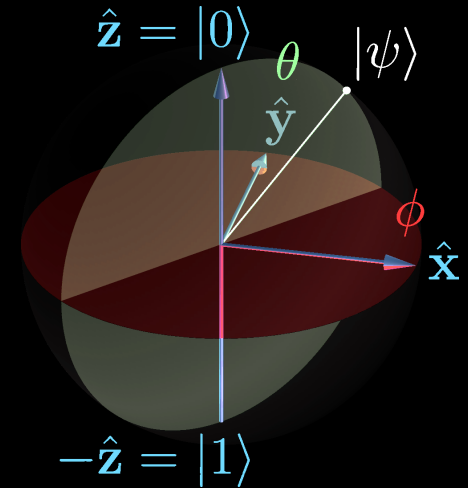
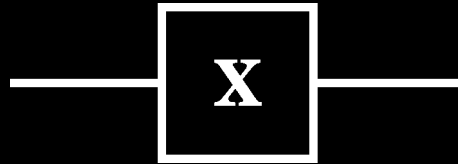
Quantum Processor

- Gates are not hardware structures
 - Gates operate on qubits “in place”
 - Gates are forces imposed on qubits
 - Conventional computer implements control
- Processor (ideally, one per qubit)
 - Only **thermodynamically reversible** gates
 - **No fanout**; **ancilla**

Quantum Gates: Conventional Logic

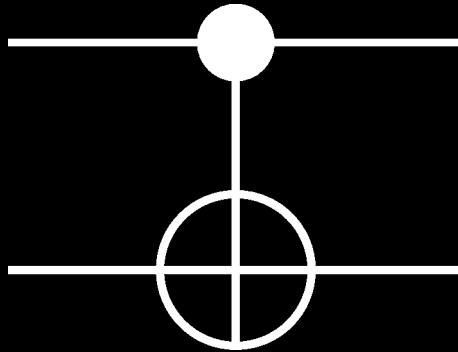
- Most quantum gates do things you could do with ordinary logic...
- Constraints:
 - Must be reversible
 - Cannot have duplicated inputs
 - Cannot have fanout
(sequential re-use is OK)

Quantum Gates: Pauli \mathbf{x}



- Pauli \mathbf{x} is also known as **NOT**
 - Rotates Bloch Sphere around X by π radians
 - Given $|\psi\rangle = a|0\rangle + b|1\rangle$,
returns $|\psi\rangle = b|0\rangle + a|1\rangle$
 - Functions like conventional **NOT**
 - \mathbf{x} is its own inverse

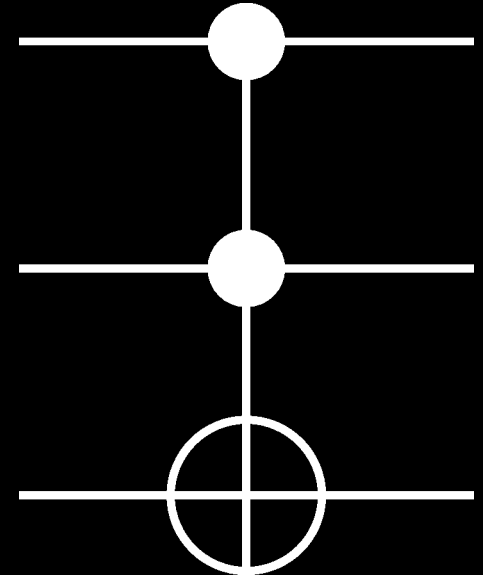
Quantum Gates: **CNOT**



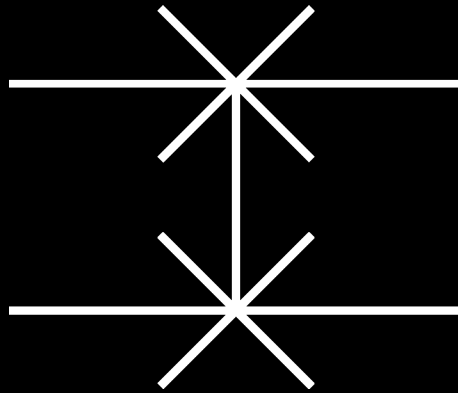
- **CNOT** is the **Controlled NOT** gate
 - Top input is control, passes thru unchanged
 - Bottom input is inverted where control is 1
 - Both inputs can't be the same qubit
 - Similar to conventional **XOR** gate

Quantum Gates: CCNOT

- CCNOT is the **Controlled Controlled NOT** gate, also known as **Toffoli** gate
 - A classical universal gate
 - Top two inputs pass unchanged
 - No two inputs can be the same qubit
 - Behaves like $C = (A \text{ AND } B) \text{ XOR } C$



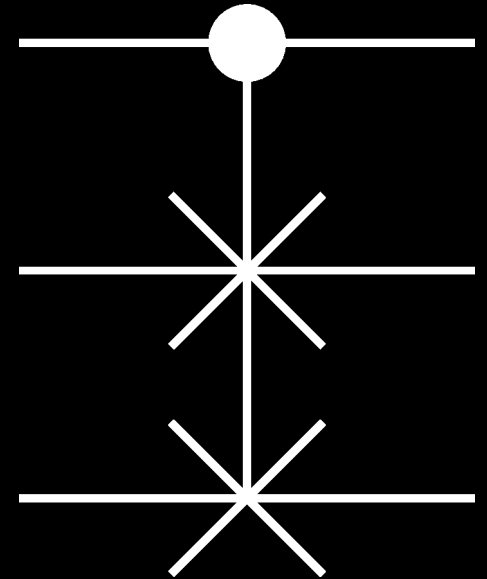
Quantum Gates: **SWAP**



- **SWAP** exchanges the values of two qubits
 - Seems pointless...
but this is a **reversible assignment**
 - This is also how to *move* qubits to near other qubits so they can interact
 - Both inputs can't be the same qubit

Quantum Gates: **CSWAP**

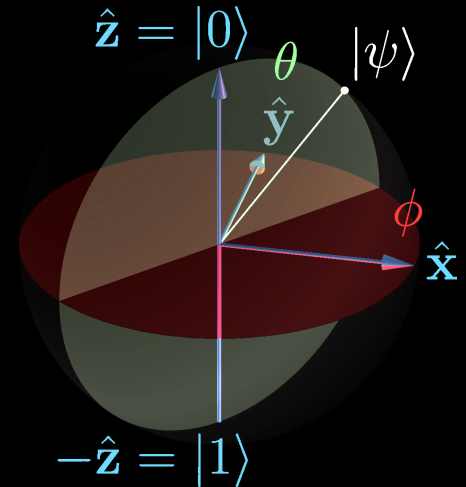
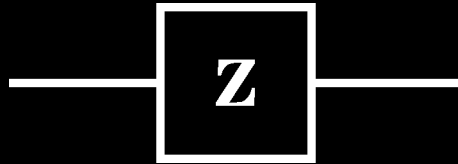
- **CSWAP** is the **Controlled SWAP**, also known as **Fredkin** gate
 - A classical universal gate... and *billiard-ball* conservative
 - Top input passes unchanged
 - No two inputs can be the same qubit
 - Behaves like paired conventional **MUXes**



Quantum Gates: Phase Operations

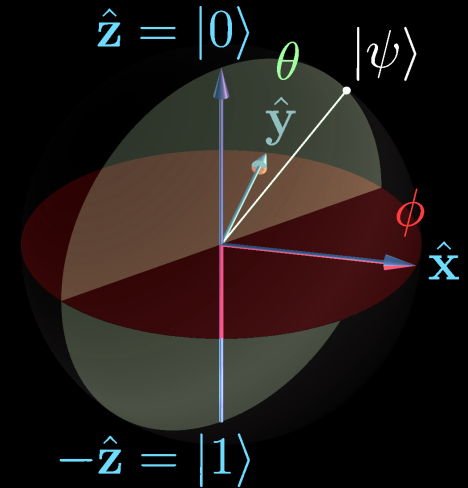
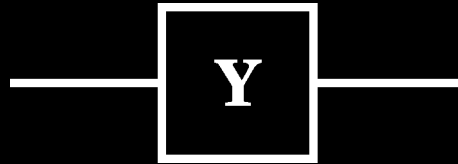
- Some operations are specific to having two-dimensional (complex) representations, as in PDFs of superposed values
- Precision of phase operations?
 - 180° rotations
 - Arbitrary rotations of unspecified precision are supported in some quantum computers

Quantum Gates: **Pauli z**



- Pauli **z** flips phase sign
 - Rotates Bloch Sphere around Z by π radians
 - Given $|\psi\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$, returns $|\psi\rangle = \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle)$
 - Doesn't alter measured value
 - **z** is its own inverse

Quantum Gates: Pauli y

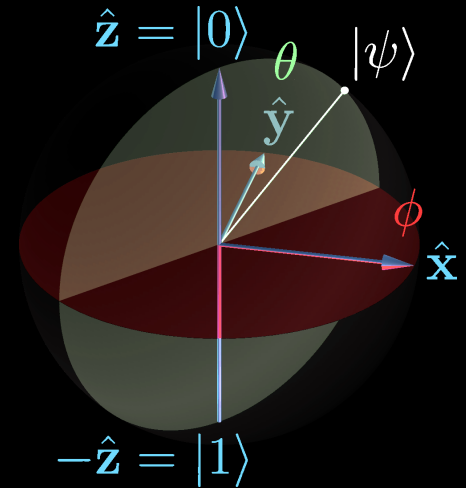
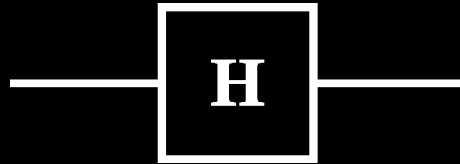


- Pauli y like combined x and z
 - Rotates Bloch Sphere around Y by π radians
 - Given $|\psi\rangle = a|0\rangle + b|1\rangle$, returns $|\psi\rangle = ia|1\rangle - ib|0\rangle$
 - y is its own inverse

Quantum Gates: Entangled Operations

- Initialization of a qubit is limited:
 - Only conventional, non-superposed, 0 or 1;
no superposed initializers
 - Often restricted to start of computation
- **All the conventional and phase operations also work on entangled superpositions**

Quantum Gates: Hadamard



- **Hadamard** transforms 0 or 1 into equiprobable superposition
- On Bloch Sphere, like rotate **y** by $\pi/2$ followed by rotate **x** by π
- **H** can be an n -ary operator, entangling n ways
- **H** is its own inverse

Quantum Gates: Hadamard

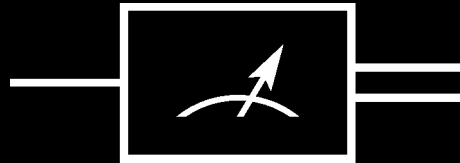
- Equiprobable superpositions created by the Hadamard operator are the primary parallel data structure
- Applying **H** to E qubits is essentially producing 2^E superposed E -bit values from $0..(2^E - 1)$
 - Like initializing v on SIMD PEs with `iprocs`
 - Operations on v have parallelism width 2^E

Parallel processing without parallel hardware!

Universal Quantum Gates

- Various options...
 - Rotation in X, Y, Z + Phase + CNOT
 - Clifford set (CNOT, H, S) + T gate
 - Toffoli + H gate
 - Deutsch gate... *which nobody uses*
- Technically, the set of possible quantum gates is uncountable, so any finite sequence of gates only approximates...

Quantum Gates: **Measurement**



- **Measurement** collapses a superposition
 - Superposed PDF is **randomly** sampled
 - Superposed qubit becomes either 0 or 1 (two output lines signify conventional 0/1)
 - PDFs of all entangled qubits prune cases where this qubit was not as measured

Matrix Representations

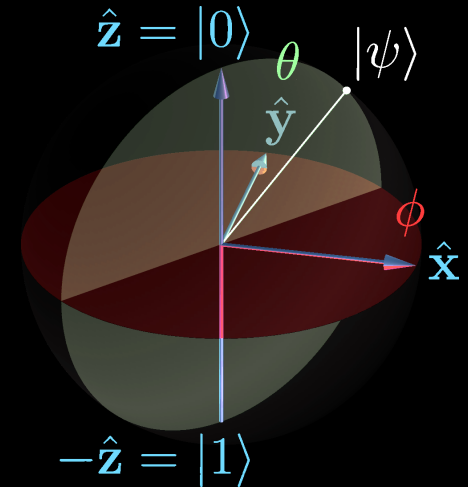
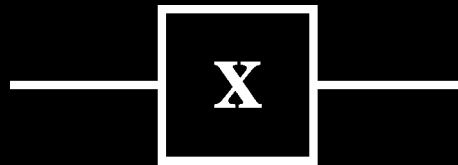
- A single bit value is $|0\rangle = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$ or $|1\rangle = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$
- A single qubit is: $|a\rangle = v_0|0\rangle + v_1|1\rangle \rightarrow \begin{bmatrix} v_0 \\ v_1 \end{bmatrix}$
- The value of a pair of qubits is:
$$|\psi\rangle = v_{00}|00\rangle + v_{01}|01\rangle + v_{10}|10\rangle + v_{11}|11\rangle \rightarrow \begin{bmatrix} v_{00} \\ v_{01} \\ v_{10} \\ v_{11} \end{bmatrix}$$

Quantum Operators are Unitary Matrix Operations

- A unitary matrix is a complex square matrix whose inverse is its conjugate transpose
- Each gate acting on n qubits is $2^n \times 2^n$
- Gate A followed by B is the same as gate $B \cdot A$
- Tensor/Kronecker product for gates in parallel
- Any unitary can be converted to a set of gates each acting on either one or two qubits
- Measurement is not a unitary operation, and it is not reversible

Quantum Gates: Pauli **x**

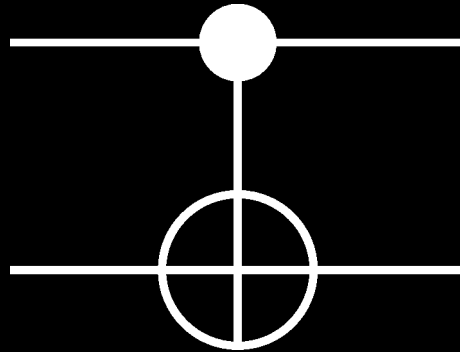
$$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$$



- Pauli **x** is also known as **NOT**
 - Rotates Bloch Sphere around X by π radians
 - Given $|\psi\rangle = a|0\rangle + b|1\rangle$, returns $|\psi\rangle = b|0\rangle + a|1\rangle$
 - Functions like conventional **NOT**
 - **x** is its own inverse

Quantum Gates: **CNOT**

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

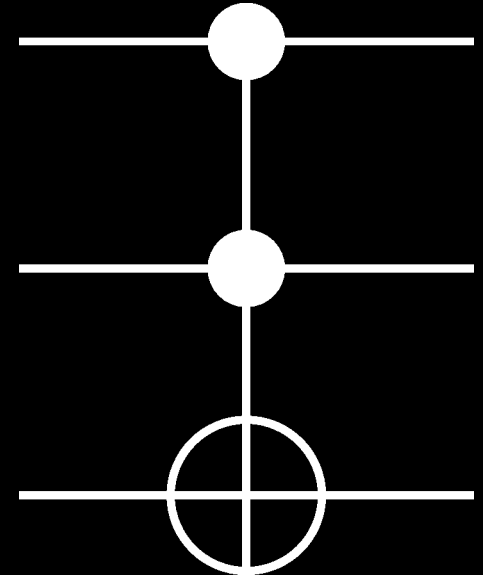


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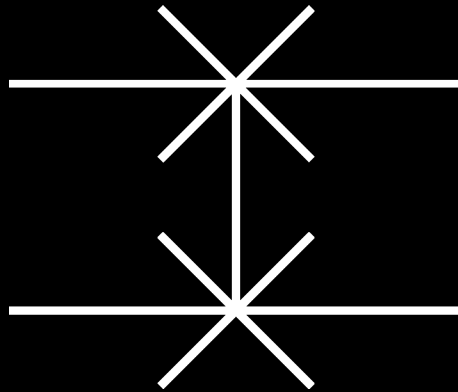
$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}$$

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 - A classical universal gate
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 - Behaves like **C = (A AND B) XOR C**



Quantum Gates: **SWAP**

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

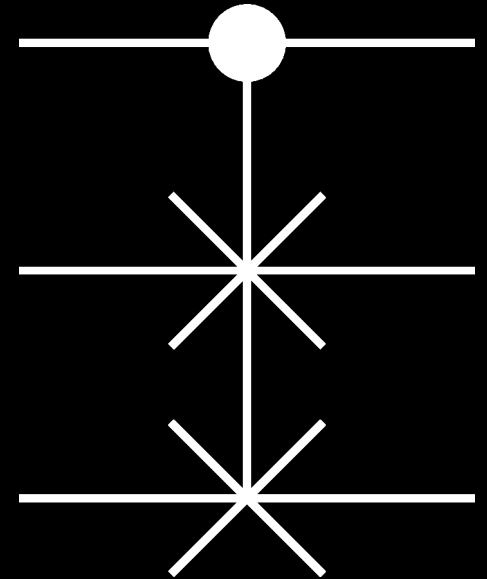


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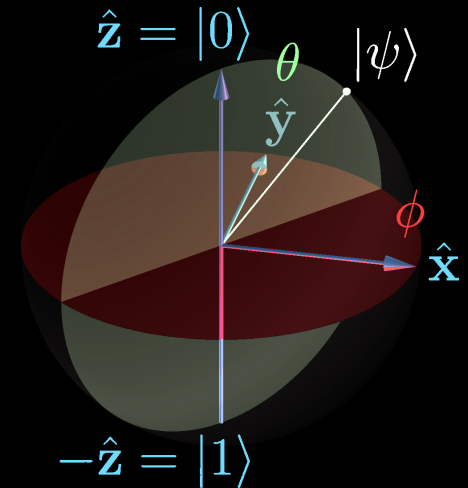
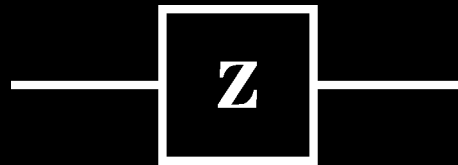
$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

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Quantum Gates: **Pauli z**

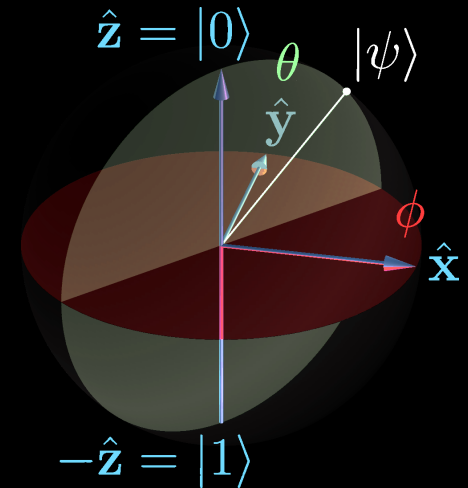
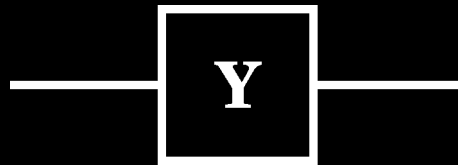
$$\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$$



- Pauli **z** flips phase sign
 - Rotates Bloch Sphere around Z by π radians
 - Given $|\psi\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$, returns $|\psi\rangle = \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle)$
 - Doesn't alter measured value
 - **z** is its own inverse

Quantum Gates: Pauli y

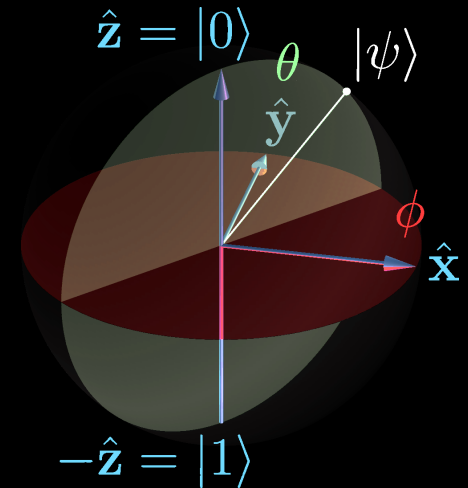
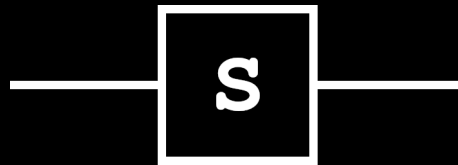
$$\begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}$$



- Pauli y like combined x and z
 - Rotates Bloch Sphere around Y by π radians
 - Given $|\psi\rangle = a|0\rangle + b|1\rangle$, returns $|\psi\rangle = ia|1\rangle - ib|0\rangle$
 - y is its own inverse

Quantum Gates: **Phase**

$$\begin{bmatrix} 1 & 0 \\ 0 & i \end{bmatrix}$$



- Phase shift **S** by i
- There is also a **P** (ψ) gate that shifts by $e^{i\psi}$ instead of i
- **P** ($\pi/4$) is also known as **T**
- There are parametric rotations about X, Y, Z
- The accuracy of ψ , etc. are unspecified...

Quantum Gates: Hadamard

$$\frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \quad \text{---} \boxed{\text{H}} \text{---}$$

- Two-qubit **Hadamard** is:

$$H_2 = H \otimes H = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \otimes \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{bmatrix}$$

- Applying to two 0 qubits:

$$H_2|00\rangle = \frac{1}{2} \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{bmatrix} \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \end{bmatrix} = \frac{1}{2}|00\rangle + \frac{1}{2}|01\rangle + \frac{1}{2}|10\rangle + \frac{1}{2}|11\rangle = \frac{|00\rangle + |01\rangle + |10\rangle + |11\rangle}{2}$$

Quantum Javascript

- **Q.js** drag-and-drop simulator

<https://quantumjavascript.app/playground.html>

The screenshot shows the Quantum Javascript (Q.js) web application in a browser. The interface includes a sidebar with navigation links, a main content area with a quantum circuit editor, and a live probability results section.

Quantum Javascript

Q is a quantum circuit simulator, drag-and-drop circuit editor, and powerful JavaScript library that runs right here in your web browser. There's nothing to install and nothing to configure, so jump right in and experiment. (Q recently celebrated our one-year anniversary. You can read the corresponding post on Medium, the discussion on Hacker News, and the thread on Reddit.)

Here's your first quantum circuit—a Bell state. It uses superposition and entanglement to calculate. (And here's how to make one yourself.) Tap and drag the tiles around to get a feel for the Q editor. It's easy to use on both desktop and mobile devices. Made a mistake? Just tap the Undo button.

Quantum Circuit Editor:

- Top bar: H, X, Y, Z, P, T gates.
- Buttons: Lock, Undo, Redo, Clear, Save.
- Circuit diagram: 4 qubits (0, 1, 2, 3). Qubit 1 has an H gate, followed by a CNOT gate with qubit 2 as the target. Qubit 2 has an X gate.

This circuit is accessible in your JavaScript console as `document.getElementById('example').circuit`

Live probability results

Edit the code above and watch the probability results update in realtime.

Qubit State	Chance
1 0000>	25% chance
2 0001>	0% chance
3 0010>	0% chance
4 0011>	0% chance
5 0100>	25% chance
6 0101>	0% chance
7 0110>	0% chance
8 0111>	0% chance
9 1000>	25% chance
10 1001>	0% chance
11 1010>	0% chance
12 1011>	0% chance
13 1100>	25% chance
14 1101>	0% chance
15 1110>	0% chance
16 1111>	0% chance

Free and open-source

Q is free to use, our code is open-source, and our API is heavily documented. Still a quantum novice? Each page of API documentation includes simple explanations of basic quantum concepts to get you up to speed quickly. This makes Q ideal for the classroom as well as autodidacts at home. Q just might be the most accessible quantum circuit suite in the world. Join our project on GitHub at <https://github.com/stewdio/q.js> and drop a link to Q's website <https://quantumjavascript.app> on social media with the hashtag #Qjs. Let's make quantum computing accessible!

MuqcsCraft

- MuqcsCraft

<https://mjmcguffin.github.io/MuqcsCraft/>

MuqcsCraft

https://mjmcguffin.github.io/MuqcsCraft/?circuit=[{"cols":["H"],["*"],["X"],["H"]}]

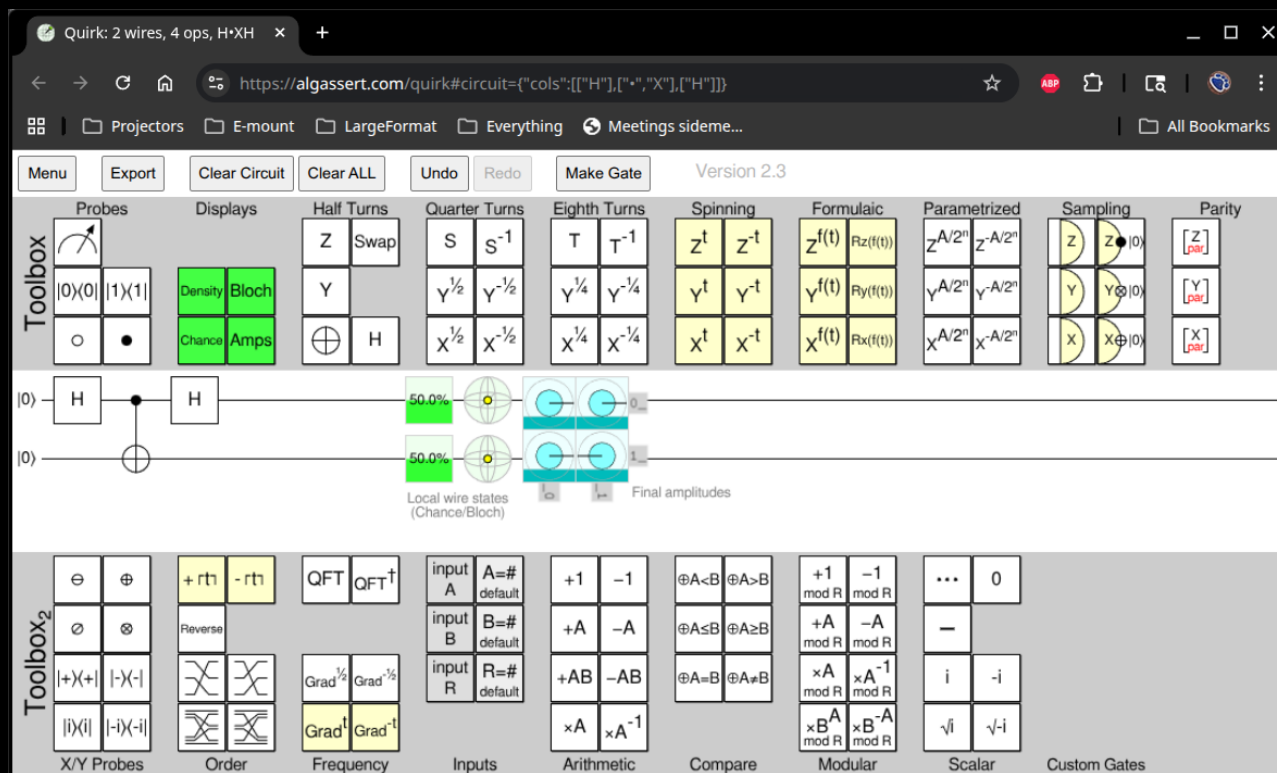
Welcome to **MuqcsCraft** [source code] [video explained] [paper], an open-source graphical simulator and visualizer for quantum circuits, built on top of the **Muqcs** library.

● ☐ Overlay
○ ☐ Display
☐ Options

☐ X ☐ Y ☐ Z ☐ $X^{1/2}$ ☐ $Y^{1/2}$ ☐ $Z^{1/2}$ ☐ $X^{1/4}$ ☐ $Y^{1/4}$ ☐ $Z^{1/4}$ ☐ X^k ☐ Y^k ☐ Z^k ☐ Ph ☐ **GP**
☐ I ☐ \otimes ☐ H ☐ $X^{-1/2}$ ☐ $Y^{-1/2}$ ☐ $Z^{-1/2}$ ☐ $X^{-1/4}$ ☐ $Y^{-1/4}$ ☐ $Z^{-1/4}$ ☐ R_x ☐ R_y ☐ R_z ☐ Z_0 ☐ Z_1 ☐ Z_2 ☐ Z_3 ☐ Z_4 ☐ Z_5 ☐ Z_6 ☐ Z_7 ☐ Z_8 ☐ Z_9 ☐ Z_{10} ☐ Z_{11} ☐ Z_{12} ☐ Z_{13} ☐ Z_{14} ☐ Z_{15} ☐ Z_{16} ☐ Z_{17} ☐ Z_{18} ☐ Z_{19} ☐ Z_{20} ☐ Z_{21} ☐ Z_{22} ☐ Z_{23} ☐ Z_{24} ☐ Z_{25} ☐ Z_{26} ☐ Z_{27} ☐ Z_{28} ☐ Z_{29} ☐ Z_{30} ☐ Z_{31} ☐ Z_{32} ☐ Z_{33} ☐ Z_{34} ☐ Z_{35} ☐ Z_{36} ☐ Z_{37} ☐ Z_{38} ☐ Z_{39} ☐ Z_{40} ☐ Z_{41} ☐ Z_{42} ☐ Z_{43} ☐ Z_{44} ☐ Z_{45} ☐ Z_{46} ☐ Z_{47} ☐ Z_{48} ☐ Z_{49} ☐ Z_{50} ☐ Z_{51} ☐ Z_{52} ☐ Z_{53} ☐ Z_{54} ☐ Z_{55} ☐ Z_{56} ☐ Z_{57} ☐ Z_{58} ☐ Z_{59} ☐ Z_{60} ☐ Z_{61} ☐ Z_{62} ☐ Z_{63} ☐ Z_{64} ☐ Z_{65} ☐ Z_{66} ☐ Z_{67} ☐ Z_{68} ☐ Z_{69} ☐ Z_{70} ☐ Z_{71} ☐ Z_{72} ☐ Z_{73} ☐ Z_{74} ☐ Z_{75} ☐ Z_{76} ☐ Z_{77} ☐ Z_{78} ☐ Z_{79} ☐ Z_{80} ☐ Z_{81} ☐ Z_{82} ☐ Z_{83} ☐ Z_{84} ☐ Z_{85} ☐ Z_{86} ☐ Z_{87} ☐ Z_{88} ☐ Z_{89} ☐ Z_{90} ☐ Z_{91} ☐ Z_{92} ☐ Z_{93} ☐ Z_{94} ☐ Z_{95} ☐ Z_{96} ☐ Z_{97} ☐ Z_{98} ☐ Z_{99} ☐ Z_{100} ☐ Z_{101} ☐ Z_{102} ☐ Z_{103} ☐ Z_{104} ☐ Z_{105} ☐ Z_{106} ☐ Z_{107} ☐ Z_{108} ☐ Z_{109} ☐ Z_{110} ☐ Z_{111} ☐ Z_{112} ☐ Z_{113} ☐ Z_{114} ☐ Z_{115} ☐ Z_{116} ☐ Z_{117} ☐ Z_{118} ☐ Z_{119} ☐ Z_{120} ☐ Z_{121} ☐ Z_{122} ☐ Z_{123} ☐ Z_{124} ☐ Z_{125} ☐ Z_{126} ☐ Z_{127} ☐ Z_{128} ☐ Z_{129} ☐ Z_{130} ☐ Z_{131} ☐ Z_{132} ☐ Z_{133} ☐ Z_{134} ☐ Z_{135} ☐ Z_{136} ☐ Z_{137} ☐ Z_{138} ☐ Z_{139} ☐ Z_{140} ☐ Z_{141} ☐ Z_{142} ☐ Z_{143} ☐ Z_{144} ☐ Z_{145} ☐ Z_{146} ☐ Z_{147} ☐ Z_{148} ☐ Z_{149} ☐ Z_{150} ☐ Z_{151} ☐ Z_{152} ☐ Z_{153} ☐ Z_{154} ☐ Z_{155} ☐ Z_{156} ☐ Z_{157} ☐ Z_{158} ☐ Z_{159} ☐ Z_{160} ☐ Z_{161} ☐ Z_{162} ☐ Z_{163} ☐ Z_{164} ☐ Z_{165} ☐ Z_{166} ☐ Z_{167} ☐ Z_{168} ☐ Z_{169} ☐ Z_{170} ☐ Z_{171} ☐ Z_{172} ☐ Z_{173} ☐ Z_{174} ☐ Z_{175} ☐ Z_{176} ☐ Z_{177} ☐ Z_{178} ☐ Z_{179} ☐ Z_{180} ☐ Z_{181} ☐ Z_{182} ☐ Z_{183} ☐ Z_{184} ☐ Z_{185} ☐ Z_{186} ☐ Z_{187} ☐ Z_{188} ☐ Z_{189} ☐ Z_{190} ☐ Z_{191} ☐ Z_{192} ☐ Z_{193} ☐ Z_{194} ☐ Z_{195} ☐ Z_{196} ☐ Z_{197} ☐ Z_{198} ☐ Z_{199} ☐ Z_{200} ☐ Z_{201} ☐ Z_{202} ☐ Z_{203} ☐ Z_{204} ☐ Z_{205} ☐ Z_{206} ☐ Z_{207} ☐ Z_{208} ☐ Z_{209} ☐ Z_{210} ☐ Z_{211} ☐ Z_{212} ☐ Z_{213} ☐ Z_{214} ☐ Z_{215} ☐ Z_{216} ☐ Z_{217} ☐ Z_{218} ☐ Z_{219} ☐ Z_{220} ☐ Z_{221} ☐ Z_{222} ☐ Z_{223} ☐ Z_{224} ☐ Z_{225} ☐ Z_{226} ☐ Z_{227} ☐ Z_{228} ☐ Z_{229} ☐ Z_{230} ☐ Z_{231} ☐ Z_{232} ☐ Z_{233} ☐ Z_{234} ☐ Z_{235} ☐ Z_{236} ☐ Z_{237} ☐ Z_{238} ☐ Z_{239} ☐ Z_{240} ☐ Z_{241} ☐ Z_{242} ☐ Z_{243} ☐ Z_{244} ☐ Z_{245} ☐ Z_{246} ☐ Z_{247} ☐ Z_{248} ☐ Z_{249} ☐ Z_{250} ☐ Z_{251} ☐ Z_{252} ☐ Z_{253} ☐ Z_{254} ☐ Z_{255} ☐ Z_{256} ☐ Z_{257} ☐ Z_{258} ☐ Z_{259} ☐ Z_{260} ☐ Z_{261} ☐ Z_{262} ☐ Z_{263} ☐ Z_{264} ☐ Z_{265} ☐ Z_{266} ☐ Z_{267} ☐ Z_{268} ☐ Z_{269} ☐ Z_{270} ☐ Z_{271} ☐ Z_{272} ☐ Z_{273} ☐ Z_{274} ☐ Z_{275} ☐ Z_{276} ☐ Z_{277} ☐ Z_{278} ☐ Z_{279} ☐ Z_{280} ☐ Z_{281} ☐ Z_{282} ☐ Z_{283} ☐ Z_{284} ☐ Z_{285} ☐ Z_{286} ☐ Z_{287} ☐ Z_{288} ☐ Z_{289} ☐ Z_{290} ☐ Z_{291} ☐ Z_{292} ☐ Z_{293} ☐ Z_{294} ☐ Z_{295} ☐ Z_{296} ☐ Z_{297} ☐ Z_{298} ☐ Z_{299} ☐ Z_{300} ☐ Z_{301} ☐ Z_{302} ☐ Z_{303} ☐ Z_{304} ☐ Z_{305} ☐ Z_{306} ☐ Z_{307} ☐ Z_{308} ☐ Z_{309} ☐ Z_{310} ☐ Z_{311} ☐ Z_{312} ☐ Z_{313} ☐ Z_{314} ☐ Z_{315} ☐ Z_{316} ☐ Z_{317} ☐ Z_{318} ☐ Z_{319} ☐ Z_{320} ☐ Z_{321} ☐ Z_{322} ☐ Z_{323} ☐ Z_{324} ☐ Z_{325} ☐ Z_{326} ☐ Z_{327} ☐ Z_{328} ☐ Z_{329} ☐ Z_{330} ☐ Z_{331} ☐ Z_{332} ☐ Z_{333} ☐ Z_{334} ☐ Z_{335} ☐ Z_{336} ☐ Z_{337} ☐ Z_{338} ☐ Z_{339} ☐ Z_{340} ☐ Z_{341} ☐ Z_{342} ☐ Z_{343} ☐ Z_{344} ☐ Z_{345} ☐ Z_{346} ☐ Z_{347} ☐ Z_{348} ☐ Z_{349} ☐ Z_{350} ☐ Z_{351} ☐ Z_{352} ☐ Z_{353} ☐ Z_{354} ☐ Z_{355} ☐ Z_{356} ☐ Z_{357} ☐ Z_{358} ☐ Z_{359} ☐ Z_{360} ☐ Z_{361} ☐ Z_{362} ☐ Z_{363} ☐ Z_{364} ☐ Z_{365} ☐ Z_{366} ☐ Z_{367} ☐ Z_{368} ☐ Z_{369} ☐ Z_{370} ☐ Z_{371} ☐ Z_{372} ☐ Z_{373} ☐ Z_{374} ☐ Z_{375} ☐ Z_{376} ☐ Z_{377} ☐ Z_{378} ☐ Z_{379} ☐ Z_{380} ☐ Z_{381} ☐ Z_{382} ☐ Z_{383} ☐ Z_{384} ☐ Z_{385} ☐ Z_{386} ☐ Z_{387} ☐ Z_{388} ☐ Z_{389} ☐ Z_{390} ☐ Z_{391} ☐ Z_{392} ☐ Z_{393} ☐ Z_{394} ☐ Z_{395} ☐ Z_{396} ☐ Z_{397} ☐ Z_{398} ☐ Z_{399} ☐ Z_{400} ☐ Z_{401} ☐ Z_{402} ☐ Z_{403} ☐ Z_{404} ☐ Z_{405} ☐ Z_{406} ☐ Z_{407} ☐ Z_{408} ☐ Z_{409} ☐ Z_{410} ☐ Z_{411} ☐ Z_{412} ☐ Z_{413} ☐ Z_{414} ☐ Z_{415} ☐ Z_{416} ☐ Z_{417} ☐ Z_{418} ☐ Z_{419} ☐ Z_{420} ☐ Z_{421} ☐ Z_{422} ☐ Z_{423} ☐ Z_{424} ☐ Z_{425} ☐ Z_{426} ☐ Z_{427} ☐ Z_{428} ☐ Z_{429} ☐ Z_{430} ☐ Z_{431} ☐ Z_{432} ☐ Z_{433} ☐ Z_{434} ☐ Z_{435} ☐ Z_{436} ☐ Z_{437} ☐ Z_{438} ☐ Z_{439} ☐ Z_{440} ☐ Z_{441} ☐ Z_{442} ☐ Z_{443} ☐ Z_{444} ☐ Z_{445} ☐ Z_{446} ☐ Z_{447} ☐ Z_{448} ☐ Z_{449} ☐ Z_{450} ☐ Z_{451} ☐ Z_{452} ☐ Z_{453} ☐ Z_{454} ☐ Z_{455} ☐ Z_{456} ☐ Z_{457} ☐ Z_{458} ☐ Z_{459} ☐ Z_{460} ☐ Z_{461} ☐ Z_{462} ☐ Z_{463} ☐ Z_{464} ☐ Z_{465} ☐ Z_{466} ☐ Z_{467} ☐ Z_{468} ☐ Z_{469} ☐ Z_{470} ☐ Z_{471} ☐ Z_{472} ☐ Z_{473} ☐ Z_{474} ☐ Z_{475} ☐ Z_{476} ☐ Z_{477} ☐ Z_{478} ☐ Z_{479} ☐ Z_{480} ☐ Z_{481} ☐ Z_{482} ☐ Z_{483} ☐ Z_{484} ☐ Z_{485} ☐ Z_{486} ☐ Z_{487} ☐ Z_{488} ☐ Z_{489} ☐ Z_{490} ☐ Z_{491} ☐ Z_{492} ☐ Z_{493} ☐ Z_{494} ☐ Z_{495} ☐ Z_{496} ☐ Z_{497} ☐ Z_{498} ☐ Z_{499} ☐ Z_{500} ☐ Z_{501} ☐ Z_{502} ☐ Z_{503} ☐ Z_{504} ☐ Z_{505} ☐ Z_{506} ☐ Z_{507} ☐ Z_{508} ☐ Z_{509} ☐ Z_{510} ☐ Z_{511} ☐ Z_{512} ☐ Z_{513} ☐ Z_{514} ☐ Z_{515} ☐ Z_{516} ☐ Z_{517} ☐ Z_{518} ☐ Z_{519} ☐ Z_{520} ☐ Z_{521} ☐ Z_{522} ☐ Z_{523} ☐ Z_{524} ☐ Z_{525} ☐ Z_{526} ☐ Z_{527} ☐ Z_{528} ☐ Z_{529} ☐ Z_{530} ☐ Z_{531} ☐ Z_{532} ☐ Z_{533} ☐ Z_{534} ☐ Z_{535} ☐ Z_{536} ☐ Z_{537} ☐ Z_{538} ☐ Z_{539} ☐ Z_{540} ☐ Z_{541} ☐ Z_{542} ☐ Z_{543} ☐ Z_{544} ☐ Z_{545} ☐ Z_{546} ☐ Z_{547} ☐ Z_{548} ☐ Z_{549} ☐ Z_{550} ☐ Z_{551} ☐ Z_{552} ☐ Z_{553} ☐ Z_{554} ☐ Z_{555} ☐ Z_{556} ☐ Z_{557} ☐ Z_{558} ☐ Z_{559} ☐ Z_{560} ☐ Z_{561} ☐ Z_{562} ☐ Z_{563} ☐ Z_{564} ☐ Z_{565} ☐ Z_{566} ☐ Z_{567} ☐ Z_{568} ☐ Z_{569} ☐ Z_{570} ☐ Z_{571} ☐ Z_{572} ☐ Z_{573} ☐ Z_{574} ☐ Z_{575} ☐ Z_{576} ☐ Z_{577} ☐ Z_{578} ☐ Z_{579} ☐ Z_{580} ☐ Z_{581} ☐ Z_{582} ☐ Z_{583} ☐ Z_{584} ☐ Z_{585} ☐ Z_{586} ☐ Z_{587} ☐ Z_{588} ☐ Z_{589} ☐ Z_{590} ☐ Z_{591} ☐ Z_{592} ☐ Z_{593} ☐ Z_{594} ☐ Z_{595} ☐ Z_{596} ☐ Z_{597} ☐ Z_{598} ☐ Z_{599} ☐ Z_{600} ☐ Z_{601} ☐ Z_{602} ☐ Z_{603} ☐ Z_{604} ☐ Z_{605} ☐ Z_{606} ☐ Z_{607} ☐ Z_{608} ☐ Z_{609} ☐ Z_{610} ☐ Z_{611} ☐ Z_{612} ☐ Z_{613} ☐ Z_{614} ☐ Z_{615} ☐ Z_{616} ☐ Z_{617} ☐ Z_{618} ☐ Z_{619} ☐ Z_{620} ☐ Z_{621} ☐ Z_{622} ☐ Z_{623} ☐ Z_{624} ☐ Z_{625} ☐ Z_{626} ☐ Z_{627} ☐ Z_{628} ☐ Z_{629} ☐ Z_{630} ☐ Z_{631} ☐ Z_{632} ☐ Z_{633} ☐ Z_{634} ☐ Z_{635} ☐ Z_{636} ☐ Z_{637} ☐ Z_{638} ☐ Z_{639} ☐ Z_{640} ☐ Z_{641} ☐ Z_{642} ☐ Z_{643} ☐ Z_{644} ☐ Z_{645} ☐ Z_{646} ☐ Z_{647} ☐ Z_{648} ☐ Z_{649} ☐ Z_{650} ☐ Z_{651} ☐ Z_{652} ☐ Z_{653} ☐ Z_{654} ☐ Z_{655} ☐ Z_{656} ☐ Z_{657} ☐ Z_{658} ☐ Z_{659} ☐ Z_{660} ☐ Z_{661} ☐ Z_{662} ☐ Z_{663} ☐ Z_{664} ☐ Z_{665} ☐ Z_{666} ☐ Z_{667} ☐ Z_{668} ☐ Z_{669} ☐ Z_{670} ☐ Z_{671} ☐ Z_{672} ☐ Z_{673} ☐ Z_{674} ☐ Z_{675} ☐ Z_{676} ☐ Z_{677} ☐ Z_{678} ☐ Z_{679} ☐ Z_{680} ☐ Z_{681} ☐ Z_{682} ☐ Z_{683} ☐ Z_{684} ☐ Z_{685} ☐ Z_{686} ☐ Z_{687} ☐ Z_{688} ☐ Z_{689} ☐ Z_{690} ☐ Z_{691} ☐ Z_{692} ☐ Z_{693} ☐ Z_{694} ☐ Z_{695} ☐ Z_{696} ☐ Z_{697} ☐ Z_{698} ☐ Z_{699} ☐ Z_{700} ☐ Z_{701} ☐ Z_{702} ☐ Z_{703} ☐ Z_{704} ☐ Z_{705} ☐ Z_{706} ☐ Z_{707} ☐ Z_{708} ☐ Z_{709} ☐ Z_{710} ☐ Z_{711} ☐ Z_{712} ☐ Z_{713} ☐ Z_{714} ☐ Z_{715} ☐ Z_{716} ☐ Z_{717} ☐ Z_{718} ☐ Z_{719} ☐ Z_{720} ☐ Z_{721} ☐ Z_{722} ☐ Z_{723} ☐ Z_{724} ☐ Z_{725} ☐ Z_{726} ☐ Z_{727} ☐ Z_{728} ☐ Z_{729} ☐ Z_{730} ☐ Z_{731} ☐ Z_{732} ☐ Z_{733} ☐ Z_{734} ☐ Z_{735} ☐ $Z_{$

Quirk Circuit Simulator

- **Quirk** open source drag-and-drop simulator
<https://algassert.com/quirk>



THE QUANTUM LÄND

- Rydberg Quantum Computers & Simulators, Stuttgart** <https://thequantumlaend.de/quantum-circuit-designer/>

